

Cosmic Strings as the Source of Small-Scale Microwave Background Anisotropy

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Cosmic string networks generate cosmological perturbations actively throughout the history of the universe. Thus, the string sourced anisotropy of the cosmic microwave background is not affected by Silk damping as much as the anisotropy seeded by inflation. The spectrum of perturbations generated by strings does not match the observed CMB spectrum on large angular scales ($\ell < 1000$) and is bounded to contribute no more than 10% of the total power on those scales. However, when this bound is marginally saturated, the anisotropy created by cosmic strings on small angular scales $\ell \gtrsim 2000$ will dominate over that created by the primary inflationary perturbations. This range of angular scales in the CMB is presently being measured by a number of experiments; their results will test this prediction of cosmic string networks soon.

I. INTRODUCTION

In the past decade, a series of experiments, in particular the Wilkinson Microwave Anisotropy Probe (WMAP) [1], have measured the anisotropy in the cosmic microwave background (CMB) radiation with extraordinary precision. The data from these experiments have helped to usher in the era of precision cosmology. Most of the cosmological results that have been obtained from these experiments have been derived from the microwave anisotropy at relatively large angular scales. The remarkable agreement between the angular power spectrum of these data and the predictions of the adiabatic inflationary scenario have established the empirical success of inflationary cosmology.

Cosmic strings, though ruled out as the origin of cosmological structure, have recently enjoyed a renaissance. This renewed popularity has been brought about by the recognition that a variety of string theory-motivated and hybrid models for inflation generically predict the formation of cosmic string networks [2–15]. Strings are limited to producing less than about 10% of the primordial CMB anisotropy [16–22], though it was shown in [22, 23] that CMB data can actually favor a contribution from strings if the inflationary spectrum is exactly Harrison-Zeldovich ($n_s = 1$); this corresponds to a string tension ($G\mu$) between 4×10^{-7} and 6×10^{-7} for a standard set of string network parameters.

The B (i.e., curl) mode polarization in the CMB caused by the active perturbations of a cosmic string network has a spectrum distinct from those expected either from inflationary gravity waves or the lensing of E (i.e., gradient) mode polarization into B mode by large scale structure. When the above bound is marginally saturated, this B mode polarization should be measurable [24–27], providing a powerful test of the presence of cosmic strings. Another consequence is the power spectrum of perturbations that strings source at large ℓ (small angular size). Cosmic string networks continually generate CMB anisotropies, both primordially through active density perturbations and subsequent to recombination through the lensing of the primary CMB light – the Kaiser-Stebbins effect (KS) [28]. The CMB anisotropy due to the KS effect alone at large ℓ is expected to decrease only as $\sim 1/\ell$ [29]. This rate of decrease is much slower than that expected for inflationary perturbations (which fall off exponentially as a function of ℓ due to Silk damping, which is due to radiative diffusion). If $G\mu$ is not too small, this large ℓ power spectrum may be measurable. It should appear as an excess above the prediction from inflationary perturbations. In particular, for $G\mu \approx 3 \times 10^{-7}$, the power created on small angular scales, $\ell \gtrsim 2000$, by cosmic strings will actually dominate over that created by the primary inflationary perturbations. This range of angular scales in the CMB is presently being measured by a number of experiments, so that this prediction of cosmic string networks will be tested soon. In this note, we present the large ℓ power spectrum due to cosmic strings.

II. COSMIC STRING MODEL

We use CMBACT [30, 31], a modified version of CMBFAST [32], to produce the string sourced anisotropy spectra. The model, described in Refs. [20, 31, 33], is based on representing the cosmic string network as a collection of moving straight string segments. In brief, there are two important length scales in this model: ξ , the length of a string

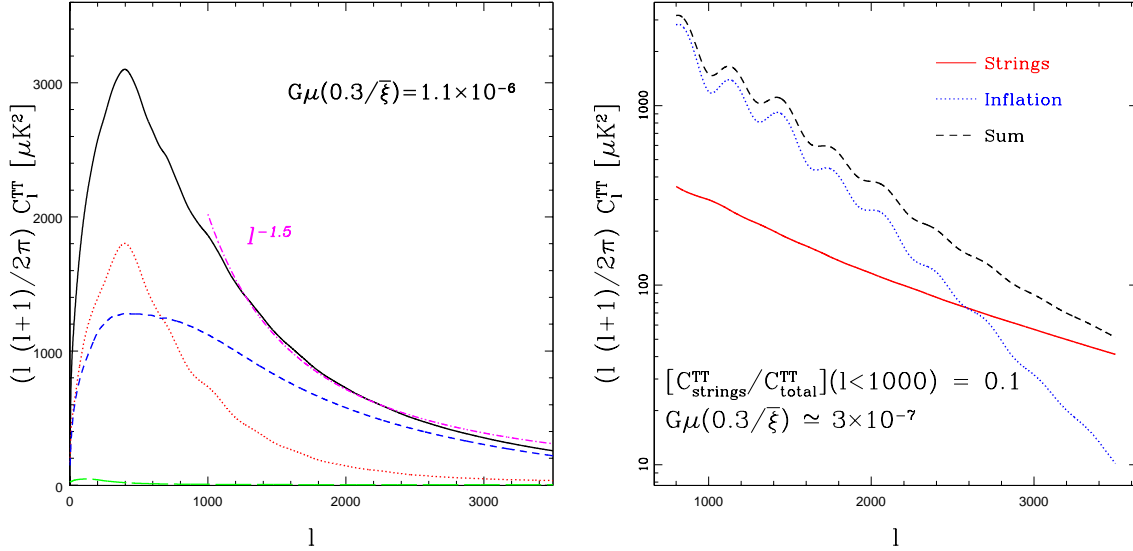


FIG. 1: *Left*: The TT power sourced by a cosmic string network with $G\mu = 1.1 \times 10^{-6}$; average coherence length $\xi \simeq 0.2$ (measured in units of the horizon size); rms velocity near $v = 0.2c$; and average wiggleness parameter $\alpha = 1.3$. The solid black line is the total power. The red dotted line is the power due to scalar perturbations, the blue dashed line represents the vector mode perturbations. The (green) long dashed line shows the (negligible) contribution from tensor modes. Note that vector modes dominate above $\ell \simeq 800$, a distinctively stringy effect. The magenta dash-dotted line shows the $\ell^{-1.5}$ fitting formula. *Right*: Contributions from strings (solid red), inflation (blue dot) (including lensing, from CAMB [41]), and their combination (black dash) at high- ℓ . The string contribution satisfies the 10% bound on total power imposed on large angular scales.

segment, which represents the typical length of roughly straight segments in a full network; and $\bar{\xi}$, the typical length between two string segments, which sets the number density of strings in a given volume ($N_s \propto 1/\bar{\xi}^2$). We use the Velocity-dependent One-Scale Model (VOS) [34] to evolve the network length-scales and density. In the simplest and most relevant cases, $\xi = \bar{\xi}$. With these parameters set, we average over a set of randomized realizations of the network approximated as a set of straight string segments. This model was introduced in [35], based on the approach suggested in [36], and was developed into its present form in [31, 37]. The overall normalization of the spectrum has a simple dependence on the string tension and number density:

$$C_\ell^{\text{strings}} \propto N_s (G\mu)^2 \propto \left(\frac{G\mu}{\xi} \right)^2. \quad (1)$$

Lower reconnection probability [38] for cosmic strings will rescale the amplitude of this spectrum, but will not change its shape. Although this model assumes a single tension cosmic string network, the results described here should generally apply for more complex multi-tension string network models of the sort that may be produced in the aftermath of brane inflation [13, 39, 40].

Fig. 1 shows our result. The dominance of vector modes (the blue dashed line in the left panel) for $\ell \gtrsim 800$ is an effect that is a distinctive signature of cosmic strings. As we show with the magenta, dash-dotted line, the string spectrum at $1000 < \ell < 3500$ – where vector-sourced perturbations start to dominate – is well approximated by a $\ell^{-1.5}$ fall off. This can be captured by a simple fitting formula:

$$(\ell(\ell+1)/2\pi) C_\ell^{TT}[\text{strings}] \simeq 500 \left(\frac{2000}{\ell} \right)^{1.5} \left(\frac{G\mu}{1.1 \times 10^{-6}} \right)^2 \quad \text{for } \ell \gtrsim 1000. \quad (2)$$

We find that towards the very high ℓ end of the considered range, i.e. at $\ell > 3000$, the fall off is better described by ℓ^{-1} , in agreement with the pure KS contribution analytically predicted in [29]. At smaller ℓ , the residual fluctuations from the last-scattering surface are non-negligible leading to a ℓ^{-2} fall off in the $1000 < \ell < 2000$ range.

The right panel in Fig. 1 shows the high- ℓ power sourced by strings relative to the inflationary contribution. The string spectrum's amplitude is set by saturating the observational bound: it accounts for 10% of power for $\ell < 1000$.

The spectrum in Fig. 1 should not be taken as the unique prediction of the C_ℓ spectrum from strings, but as a representative example of what one can get for a reasonably motivated string network. It corresponds to particular values of string model parameters, such as wiggleness, coherence length, and rms velocity. It also relies on the “moving

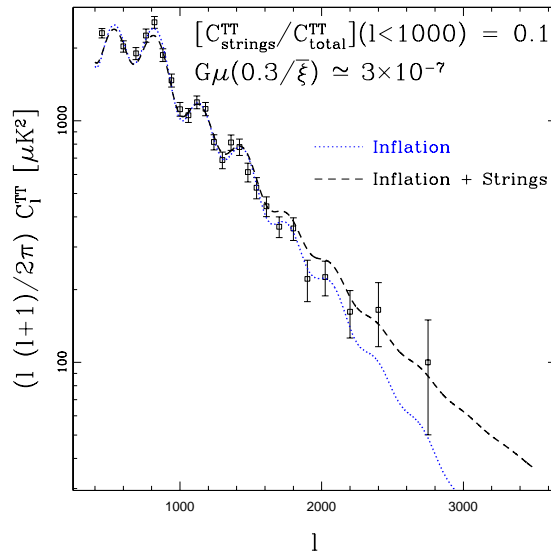


FIG. 2: The predicted high ℓ CMB anisotropy in the ACBAR range, plotted against the latest data from the ACBAR experiment. The dotted blue line is the inflationary prediction alone (including lensing, from the software package CAMB [41]); the dashed black line includes the contribution from a cosmic string network. The amplitude fitting has been done roughly, by eye, to match the two theoretical curves with the second ACBAR data point; the cosmological parameters are all those of the WMAP best fit.

segments” approximation used in CMBACT. This model is designed to describe statistical properties of scaling string networks. For instance, it can be used to calculate CMB power spectra, but cannot make a sky map of string network effects. Real string simulations that capture more of the physics of networks—such as their curvature and loops—are too computationally costly to be used over many expansion times. The segments model has been shown to match CMB spectra from full simulations reasonably well over the scales where they can be compared (for a fuller discussion, see Refs. [20, 31, 33]).

While varying the string tension, $G\mu$, simply renormalizes the spectrum, changing the other parameters can redistribute the power between the large and small scales. Generally, smaller velocities and smaller coherence lengths enhance the power in vector modes at high ℓ [42]. More wiggleness tends to make strings move more slowly. This suppresses all contributions to the anisotropic stress, including the vector modes [31, 42]. For this plot, we used a model with $G\mu = 1.1 \times 10^{-6}$ with an average string coherence length of ~ 0.2 of the horizon size¹, a rms velocity of $\sim 0.2c$, and an average wiggleness parameter α of 1.3. These values are fairly close to those seen in numerical simulations (e.g. [43]), but are slightly different from those used in the default version of CMBACT; the values chosen here are those which slightly enhance the string-sourced power at high ℓ . Fractionally greater (or attenuated) power at small angular scales can be achieved with different model parameters, but the overall behavior at high ℓ is a generic feature of string networks. All cosmological parameters, *i.e.* Ω_M , h , etc, are those of the latest WMAP best fit [1].

III. CONCLUSION AND REMARKS

Cosmic strings produce power on small angular scales because they are *active* sources that continue contributing to the anisotropy after the last scattering. For that reason they evade Silk damping, *i.e.* the erasure of anisotropies on small scales due to the finite thickness of the last scattering surface. A network of cosmic strings with a tension near the present observational bound of $G\mu \lesssim 6 \times 10^{-7}$ can dominate the power spectrum of CMB fluctuations in the strongly Silk-damped regime ($\ell > 2000$) of the microwave background anisotropy, creating an apparent excess of power over what is expected from an inflationary adiabatic perturbation spectrum. This high ℓ regime is accessible to

¹ The coherence length of infinite strings is typically of the order of the horizon size at each epoch. A smaller *average* coherence scale comes about when a significant fraction of the network density is present in the form of large string loops. The fraction of string density in loops grows for smaller values of $G\mu$.

existing fine scale resolution experiments like the Cosmic Background Imager (CBI) [44] and the Arcminute Cosmology Bolometer Array Receiver (ACBAR) [45] now, and will soon be measured very accurately by experiments like the South Pole Telescope [46] and the Atacama Cosmology Telescope [47]. It is interesting to note that these experiments' published data already show some hints of excess power in the high-multipole range; see Fig. 2 for a rough comparison with the data from ACBAR. Although we have not done a statistical analysis, the preliminary results presented here suggest that cosmic strings with $G\mu(0.3/\xi) \simeq 3 \times 10^{-7}$ could contribute enough power to account for the excess over inflation suggested by the ACBAR data at $\ell \gtrsim 2000$ without exceeding observational bounds on string contributions at $\ell \lesssim 1000$. Excess power in the high- ℓ CMB can also be generated by other physical phenomena, including the Sunyaev-Zeldovich effect [48] and tangled primordial magnetic fields [49]. Using the SZ effect to account for any substantial excess measurable by today's experiments is problematic, however, because the amount of small-scale gravitational clustering (measured by the parameter σ_8) required to generate a large excess over the inflationary prediction via the SZ effect is in some conflict with values determined by other experiments. Tangled magnetic fields, on the other hand, are not meaningfully constrained by competing experiments, but their existence at the necessary epoch is by no means accounted for. Discovery of significant high ℓ excess power in CMB that cannot be explained by more conventional means could be taken as evidence for existence of cosmic strings with tensions near the observational bound. On the other hand, if no excess is seen at large ℓ , non-observation of this effect will provide a useful bound on the properties of any cosmic string network. Strings with tensions in this range can be searched for by some other means, such as gravitational lensing and microlensing [50], gravitational radiation bursts [51], pulsar timing or non-Gaussian step-like fluctuations in CMB temperature [52]. An especially promising signature of such strings would be a substantial B mode polarization [24–27]; for $G\mu$ around 6×10^{-7} , the B mode polarization fluctuations from strings could exceed expected power from E to B conversion by gravitational lensing by factors of a few.

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